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DISTRIBUTION AND ORIENTATION OF CARBON FIBERS IN POLYLACTIC ACID PARTS PRODUCED BY FUSED DEPOSITION MODELING

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ABSTRACT

The aim of this paper is the understanding of the fiber orientation by investigations in respect to the inner configuration of a polylactic acid matrix reinforced with short carbon fibers after a fused deposition modeling extrusion process. The final parts were analyzed by X-ray, tomography, and magnetic resonance imaging allowing a resolved orientation of the fibers and distribution within the part. The research contributes to the understanding of the fiber orientation and fiber reinforcement of fused deposition modeling parts in additive manufacturing.

INTRODUCTION

A literature review of research on fiber-reinforced polymers in additive manufacturing using mainly glass and carbon fibers showed that prior work in the field of FRPs in FDM has already been performed by [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11] investigating the direction of fiber-reinforced Fused Deposition Modeling (FDM) using carbon and glass fibers in an Acrylonitrile Butadiene Styrene (ABS) or polylactic acid (PLA) matrix and discussing the strengthening of the material as well as the fiber orientation. An overview of the increase of tensile strength and Young's modulus achieved by the above-mentioned sources using FRP in FDM is shown in Figure 1 and Figure 2. The preliminary data of Figure 1 and Figure 2 may be suggestive of trends, but due to its tentative nature we voluntarily abstained from implying any quantitative relation by fitting a regression model.

Investigations of the final part were performed using a JSM-5910 Scanning Electron Microscope

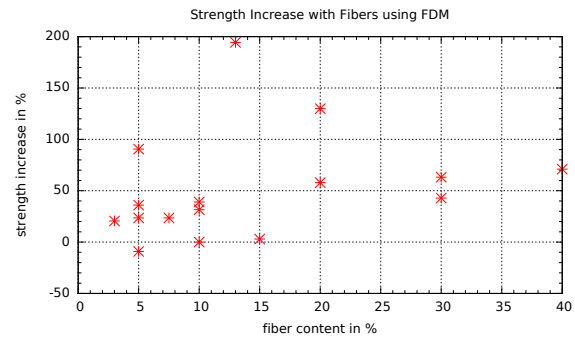


FIGURE 1. Increase of tensile strength according to literature research with different amounts of fibers.

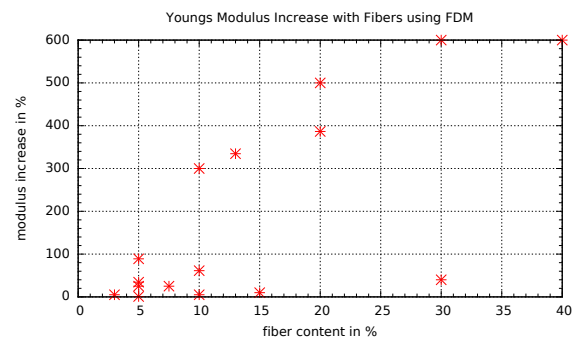


FIGURE 2. Increase of Young's modulus according to literature research with different amounts of fibers.

(SEM). Possibilities for the transmissive investigation of PLA are supported by [12] stating a continuous transmission of PLA of over 90 % at wavelengths of 250 nm and higher.

To investigate the spatial alignment, orientation and distribution density of the fibers within the printed part as well as the conformity of the printed results with the intended shape both on mesoscopic and macroscopic level, Radiological modalities like Computed 2-dimensional X-ray Radiography on photostimulated luminescence image storage plates (CR), Computed X-ray Tomography (CT) with human-grade multi-detector 128-line CT and research-grade micro-CT Scanners was performed. Finally, the material properties were explored with quantitative Magnetic Resonance Imaging (MRI) methods at 3 T.

METHODS

The parts were produced using PLA filament with 15 %_{wt} virgin short carbon-fiber content with average diameters of 7.2 μm and an average length of 100 μm . During the manufacturing process, the fiber-reinforced filament was heated over the material's glass-transition temperature and fed through a nozzle with a diameter of 400 μm . This resulted in an orientation of the carbon fibers along the path of the filament. This property could be used when aiming to reinforce the product in a certain main direction.

An orthogonal cut through the layers of the FDM print of the objects was performed, followed by a polishing finish in order to visualize features of 1 μm voxel size before the SEM investigation. Due to the layer-wise orthogonal alignment of the infill, the cut showed one layer along the line produced by the FDM nozzle and one cut orthogonal to the line allowing an elaboration on the orientation in three dimensions as well as the interface between the different extrusion directions.

Moreover, SEM investigations of the fracture surface were performed after a pull-test was performed until the failure of the part. The dog bones used for this investigation were produced by the above-mentioned FDM printer under layer-wise alternation of the printing direction in order to avoid globally anisotropic material properties in the final dog bone.

The printing paths are graphically represented in Figure 3 and Figure 4. The outer paths were tracked around the object to provide a higher sur-

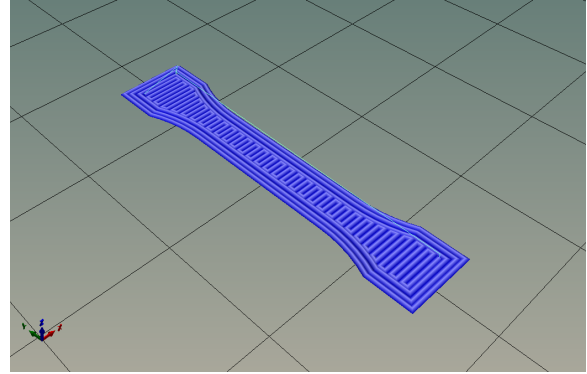


FIGURE 3. First layer geometry of the printed dog bone.

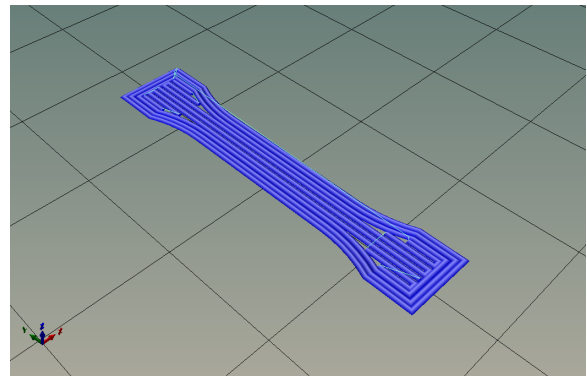


FIGURE 4. Second layer geometry of the printed dog bone.

face accuracy and a cohesion of the entire dog bone. By investigation of a single surface, cuts in two directions through the extruded filament as well as an investigation of the interface between the filament lines are possible.

This production method can be justified with the above-mentioned investigation aims of a detection of fiber orientation. Investigations aiming to find the increase of tensile strength or Young's modulus have chosen a fiber orientation entirely in longitudinal orientation.

This research contributes to the understanding of FDM processing with FRPs by observing the fiber orientation after the manufacturing and within the final part. The orientation of the fibers allows a directional reinforcement of the final part that may be manipulated on a mesoscopic level.

This material may offer susceptibility matching properties of greatest interest for Nuclear Magnetic Resonance (NMR) / nuclear MRI applications in technology as well as in medicine. In

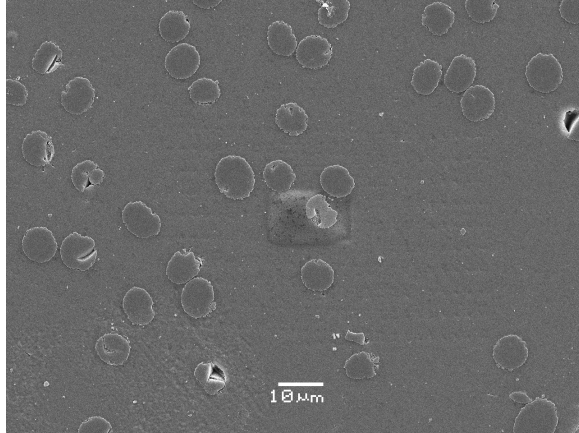


FIGURE 5. Fiber orientation and interface to the PLA in a polished cut.

their pioneering work, Lee et al. [15] showed the benefits of using Pyrolytic Graphite Foam as a passive magnetic susceptibility matching material. This material seems to have similar desirable properties and at the same time offers far greater mechanical strength whilst retaining the property of being able to be 3d-manufactured into desired shapes with readily available 3d-printers.

One possible further application to be pointed out is the individualised 3d-manufacturing of potentially medical implants. Conventional implants manufactured from non-ferromagnetic metals still retain a certain degree of resultant image artefacts in MRI and hence may hinder forthcoming examinations difficult to impossible.

Notwithstanding the tentative nature of the experience with the material and the clear implication of the strongest need for more research, the material may provide an easy to manufacture, lightweight and economically attractive solution.

RESULTS

Scanning Electron Microscopy

The polished cut through an extrusion line shows the interface between the carbon fibers and the PLA matrix in Figure 5. The interface neither exhibits gaps between the fiber and the matrix nor cracks in the matrix. The detailed view in Figure 6, nevertheless shows deformed and destroyed fibers. The bottom-right corner of the image shows a part of the matrix where the viscosity of the PLA-melt exceeded the possibilities of filling the sharp concave corners.

Significantly stronger influence can be stated for holes resulting from the manufacturing process in

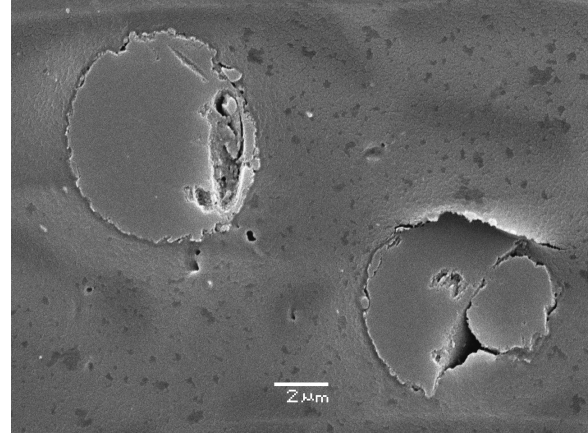


FIGURE 6. Detail view of the interface between the fibers and the PLA matrix in a polished cut.

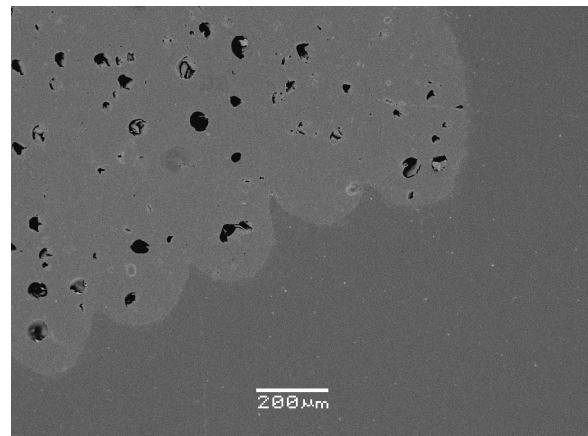


FIGURE 7. Holes in the PLA matrix in a polished cut; variations in amount and size of holes at the different layers are visible.

the FDM nozzle. The holes shown in Figure 7 result from the thermal setting of the nozzle.

The holes show a characteristic oval shape when cut longitudinally to the fiber orientation and a round shape when cut orthogonally to the fiber orientation allowing the interpretation of an ellipsoid shape with the major axis in the extrusion orientation. The same observation can be made in Figure 10.

The characteristic interface between the produced extrusion vanishes due to the remelting of the matrix polymer during the extrusion and deposition process. Intersection of differently-oriented fibers between the layers is visible in the fracture surfaces of Figure 8 which, together with Figure 9 and Figure 10, confirms again the orientation and size of the holes in the matrix material. Therefore,

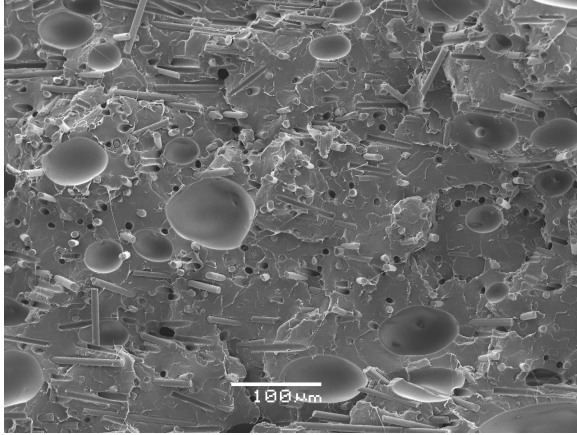


FIGURE 8. Fiber orientation according to the print direction on a fracture surface after a tensile test; orientation of the fibers in the direction of the extrusion.

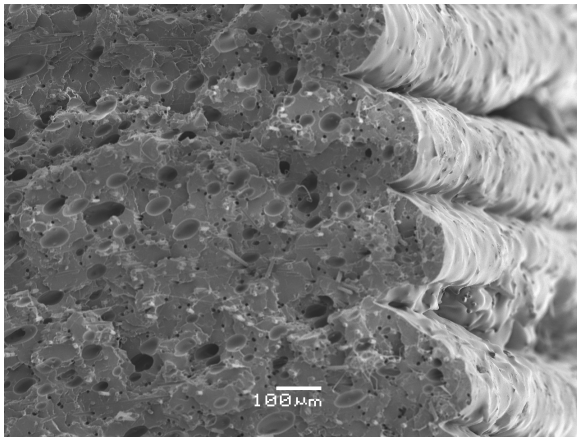


FIGURE 9. Holes in the PLA matrix on a fracture surface after a tensile test; variations in amount and size of holes at the different layers are visible.

the tensile strength is reduced by the disturbed matrix material.

Figure 8, Figure 9, and Figure 10 show the characteristic fiber orientation longitudinally to the extrusion path. Confirming the common theory of the effect of fiber orientation on tensile strength in FRP, the influence of the orientation on the fracture surfaces is shown by the high number of orthogonally oriented fibers missing in the fracture surface, whereas only 40 % of the fibers in a longitudinal orientation towards the tensile strength were pulled out of the matrix at the fracture surface.

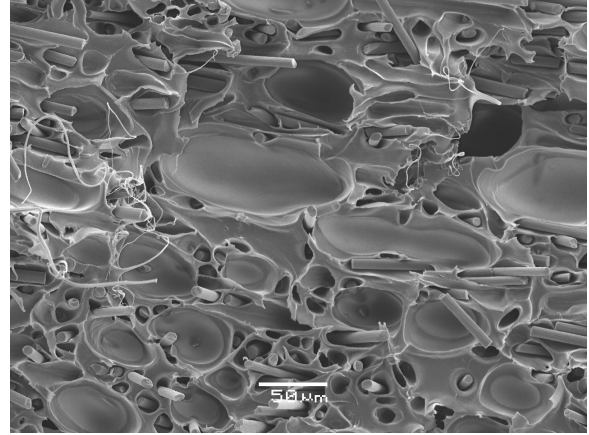


FIGURE 10. Detail of holes in the PLA matrix on a fracture surface after a tensile test; variations in orientation and size of holes at the different layers.

Radiological Imaging

In spite of all efforts and using a state of the art high end human multi-detector CT, the resolution limit for resolving fibers or even distribution densities remained too high to draw any conclusions that concur with the high professional level we desire. At the present moment, no apparent potential for using human grade multi-detector CT in determining the mesoscopic structure of materials is in our grasp. However, this may change with the rise of multi-energy and multi-beam technologies.

Cone Beam CT may provide a solution, as some manufacturers claim to provide devices with resolutions down to the order of about 10 μm on human (i.e. easily available) scanners.

Research grade micro-CT has the potential to provide deeper insight into the structure as shown in Figure 11. Clearly visible are fiber bundles, individual fibers and air inclusions in an extruded filament.

CR is proved to be most effective for this application, mostly due to its sufficient resolution, simple setup and uncomplicated availability.

Notwithstanding being at the edge of resolvability and certainly with some degree of spatial aliasing, it was possible, after optimisations using a carefully prepared honeycomb shaped geometry for the print with illumination lateral relative to the main axis of the honeycomb rhombic geometry, to work out details of the fibre bundle distribution.

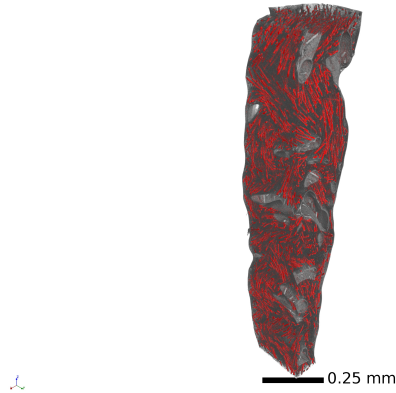


FIGURE 11. Freely extruded filament under CT investigation.

CONCLUSIONS

A conclusion can be drawn in terms of fiber orientation during the final part in strong relation to the printing orientation in the FDM process. Due to the two cycles of extrusion of the material (1) when generating the filament from granule; and (2) during the additive-manufacturing (AM) process, fibers were oriented longitudinally to the printing path.

Elipsoidal holes with the major axis in the nozzle orientation occurred in the PLA matrix with average sizes of 50 to 100 μm possibly resulting in a reduction of tensile strength. Compared to FRP in digital light processing (DLP), the size of the holes was significantly increased [16]. The distribution of fibers was therefore also influenced whereas the fibers were generally oriented in the middle of the extrusion line.

The interface between the layers was indistinct due to the remelting of material during the extrusion of the next layer allowing for a continuous matrix material. This also resulted in an interconnected orientation of longitudinally-oriented and orthogonally-oriented fibers.

The interface between the fibers and the PLA matrix was destroyed during the tensile-test. This was fatal at the layers with orthogonal fiber orientation towards the tensile strength. 40 % of all fibers in a longitudinal orientation towards the tensile strength were ripped out of the matrix at the fracture surface.

As a further line of investigation, is to proceed in investigating radiography of thin cut slices in order to minimize projective geometry and partial volume artefacts.

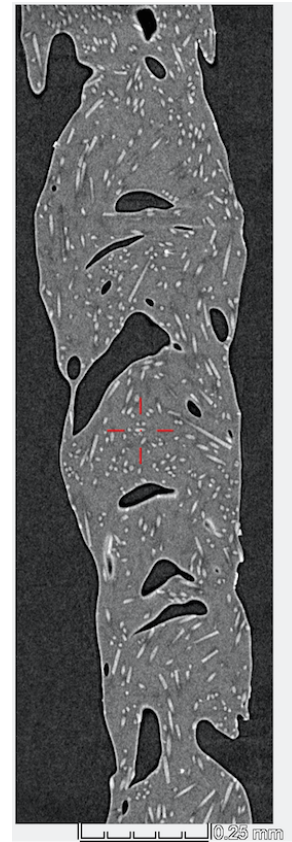


FIGURE 12. Transversal and medial lateral cut under CT investigation.

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